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The scapulo-humeral rhythm: effects of 2-D roentgen projection

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Abstract

Objective. The objective of this study is to illustrate the low accuracy of two-dimensional (2-D) X-ray projection methods for the quantification of the three-dimensional (3-D) shoulder motions.

Background. The traditional method for the quantification of the gleno-humeral motion is by means of 2-D X-ray recording. The motion was characterized by the scapulo-humeral rhythm: the ratio of the nett humeral elevation over nett scapular rotation. The method was based on the quantification of the planar projection of the spatial positions of X-ray dense structures of the scapula. The deformations introduced by the central projection method, a feature of X-ray projection, cannot be compensated for by calibration: the position of the scapula with respect to the camera setting is unknown, and skeletal landmarks of the scapula cannot uniquely be identified. The transformation from 3-D orientations to 2-D angles will, therefore, be inaccurate.

Methods. A 2-D X-ray projection of the scapula during a typical arm abduction was simulated. The 3-D motion was obtained by means of palpation and subsequent digitization of skeletal landmarks of the scapula. The 3-D positions of the recorded landmarks were projected on a plane by a simulation based on the parameters of the X-ray equipment. The scapulo-humeral rhythm was calculated for the different scapular landmarks, and for the orientation of the subject with respect to the projection axis. The results were compared with previous published scapulo-humeral rhythms.

Results. The scapulo-humeral rhythm depends both on the choice of the skeletal landmarks, used to quantify the scapular rotations, and on the orientation of the subject in the X-ray setting. The full range of results obtained from earlier published experiments could be obtained from a simulation based on a single 3-D arm abduction.

Conclusions. The 2-D scapulo-humeral rhythm, obtained from planar X-ray projection, is an inaccurate parameter to define the scapular motions.

Relevance.

The 2-D scapulo-humeral rhythm is an insensitive parameter to identify clinical disorders in the gleno-humeral motions, 3-D motion recording should be applied. Only when stringent pre-cautions are taken with respect to repeatability of positioning of the subjects, can the method be used to study intra-individual effects, e.g. the follow-up of patients during treatment.

Keywords: Shoulder; Kinematics; Scapulo-humeral rhythm; X-ray

1. Introduction

The large mobility of the arms with respect to the trunk is made possible by the shape of the gleno-humeral joint and the mobility of the scapula with respect to the thorax. About one third of the arm abduction originates from the scapular rotations relative to the thorax in the sterno-clavicular joint and the aromio-clavicular joint. Two thirds of the arm abduction originates from gleno-humeral rotations between the scapula and the humerus. Inman *et al.* [1] quantified the gleno-humeral motion using two-dimensional (2-D) X-ray projection. The ratio of the humerus rotation, $\Delta\theta_A$, over the scapular spine movement, $\Delta\theta_S$, was referred to as the 2-D scapulo-humeral rhythm $SH_{2\text{-}D}$:

$$SH_{2D} = \Delta\theta_A / \Delta\theta_S \qquad (1)$$

A summary of the $SH_{2\text{-}D}$ published since, and the methods used, are given in Table 1. The magnitude of scapulo-humeral rhythm ranges from $SH_{2\text{-}D} = 2.3$ [6] to $SH_{2\text{-}D} = 3.2$ [1], for scapular rotations quantified on the scapular spine. Saha [2] quantified the scapula rotation

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fTable 1
Literature review on two-dimensional scapulo-humeral rhythms

Author	Motion	Angle[1]	Ridge	$\Delta\theta_A/\Delta\theta_{TH}$	$\Delta\theta_A/\Delta\theta_{GH}$	$\Delta\theta_{GH}/\Delta\theta_{TH}$
Inman *et al.*[1]	ABD	0°	spine	3.25*	1.44	2.25
	ANT	0°	spine	3.20*	1.45	2.20
Saha[2]	ABD	0°	medial border	3.69	1.37	2.69*
Freedman & Munro[3]	IMP	30°	glenoid	2.54	1.65*	1.54
		30°		2.32	1.76*[2]	1.32
Doody *et al.*[4]	IMP	30°[3]	spine	2.92*	1.52*	1.92
Poppen & Walker[5]	IMP	0°	glenoid	2.27*	1.82*	1.25
Bagg & Forrest[6]	IMP	30°	spine	2.29*[4]	1.78	1.29
				2.62* ±0.24	1.62	1.62
Michiels & Grevenstein[7]	IMP	30°	glenoid	2.94	1.52*	1.94

θ_{TH}: scapula rotation; θ_{GH}: gleno-humeral rotation; θ_A: humerus elevation; ABD: abduction; ANT: anteflexion; IMP: intermediate plane of elevation (scapular plane).

*Indicating original data, the other data are derived from $\Delta\theta_A = \Delta\theta_{TH}+\Delta\theta_{GH}$.

[1]The angle represents the main registration axis of the camera with respect to the frontal (coronal) plane of the subject. 0° represents the antero-posterior view; 30° represents a rotation around a vertical axis to contra-lateral (perpendicular to the scapular plane).

[2]Elevation range between 45° and 135°.

[3]Data of Doody *et al.* [4] were recorded by means of goniometry.

[4]Data of Bagg & Forrest [6] of the full arm elevation were not consequent with the distinguished subgroups. Both the overall rhythm and the mean of the subgroups are given.

by the medial ridge of the scapula, resulting in $SH_{2\text{-}D} = 3.7$.

The position of the scapula with respect to the thorax is determined by the orientation of the clavicle, constraining the position of the acromio-clavicular (AC) joint to a sphere, and by the scapulo-thoracic gliding plane, constraining the medial border of the scapula to the thorax during normal abduction [8]. Owing to the curvature imposed by both the clavicle and the thorax, the movement of the scapula is not planar. Three-dimensional (3-D) measurements of the motions of the shoulder [9–16] illustrate this.

Consequently, the 2-D projection of the planar recorded angles is affected by the choice of the skeletal ridges tht define the scapular angle, and by the plane of projection [17]. The purpose of this study is to quantify the effect of these two factors on the $SH_{2\text{-}D}$. The 3-D kinematics of the scapula during an abduction in the scapular plane, and recorded by means of the palpation an digitization of skeletal landmarks [14–16], was used to simulate the X-ray projection of the scapular spine and the medial ridge on different vertical planes. From the projection of the ridges on these planes, the 2-D scapulo-humeral rhythm $SH_{2\text{-}D}$ was calculated.

2. Methods

In the global coordinate system the x_G-axis is pointing to the right, the y_G-axis is pointing vertically upward, and the z_G-axis is pointing vertically backward, Fig. 1. Ten 3-D posturs of the right humerus and the scapula of one subject were recorded during abduction. The plane of arm abduction was 30° anteriorly rotated with respect to the frontal plane. The postures were measured by means of palpation and subsequent digitization of skeletal landmarks: the AC joint, palpated at the dorsal end of the crevice; the angulus acromialis (AA), the dorsal angle between the acromion and the scapular spine; the trigonum spinae (TS), the intersection of the lower spinal ridge and the medial ridge of the scapula; and the angulus inferior (AI), the caudal point of the scapular ridge in the anatomical position, Fig. 1. A third order polynomial was fitted on the 3-D coordinates of the scapular landmarks, to obtain a smooth interpolated description of the motion of the skeletal landmarks.

The 3-D interpolated trajectories of the skeletal landmarks of the scapula were used to simulate the X-ray projection of the scapula during arm elevation. The geometrical centre of all coordinates of four landmarks and 10 recorded positions, i.e. the average shoulder position, was defined to be the origin of the global coordinate system. An antero-posterior X-ray recording of the motion was simulated by positioning the X-ray source at 800 mm in front of the subject [0 0 −800] and the projection plane [x_P, y_P] at 200 mm behind the subject [0 0 200], parallel with the [x_G, y_G]-plane, Fig. 1.

The four skeletal landmarks AC, AA, TS and AI marked three scapular ridges: the superior ridge of the scapular spine (TSAC), the inferior ridge of the scapular spine (TSAA), and the medial ridge of the

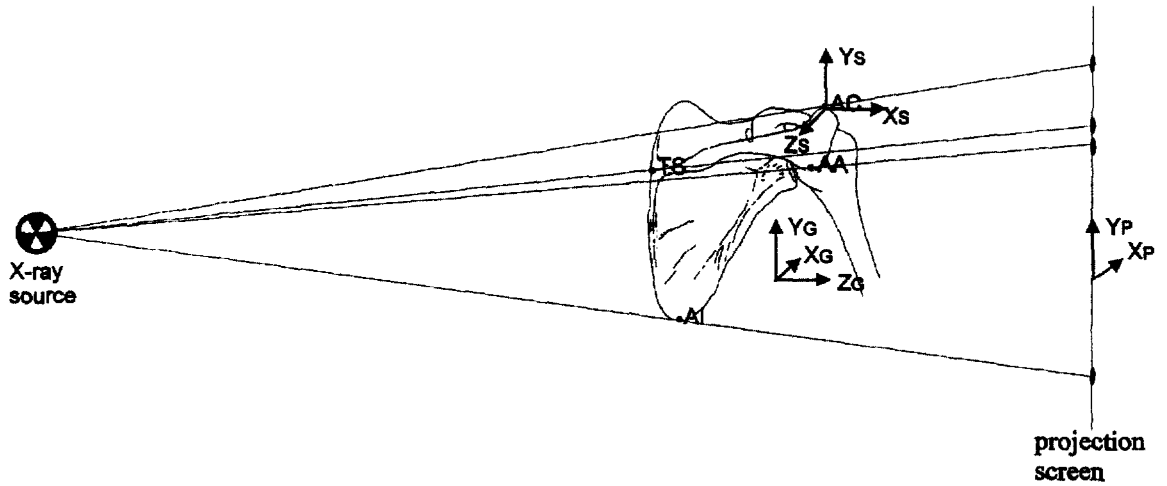

Fig. 1. Schematic simulation setting. The X-ray source at [0, 0, −800 mm], the projection screen at [0, 0, 200 mm] expressed in the global coordinate system [x_G, y_G, z_G] in millimetres. The acromio-clavicular joint, AC, the angulus acromialis, AA, trigonum spinae, TS, and the angulus inferior, AI, are palpated skeletal landmarks of the scapula, that define the scapular coordinate system [x_S, y_S, z_S]. The landmarks are projected on the projection screen [x_P, y_P].

scapula (TSAI). The effect of the different ridges on the scapulo-humeral rhythm was quantified. The projection angle of the spinal ridges was determined relative to the y_P-axis, the angle of the medial ridge was determined relative to the x_P-axis.

Also, the effect of rotation of the subject along the axial body axis on the projection, was examined by rotation of the scapular coordinates about the global y_G-axis, from −10 to +35°, and in which 0° defined the antero-posterior projection.

3. Results

The recorded orientations of the right scapula were expressed by Cardan rotations around the local axes of scapula in the y–z–x order according to Groot [15,16], Fig. 2. The x_S-axis of the scapula was defined by the vector from the TS-landmark to the AA-landmark. The y_S-axis of the scapula was defined in the plane of the AA, TS and AI landmarks perpendicular to the x_S-axis, pointing upward. The z_S-axis was defined perpendicular to the x_S and y_S-axes, pointing dorsally. The rotations were expressed with respect to the initial position in which the scapular axes were aligned with the global x_G, y_G and z_G-axes [15,16].

In the [x_P, y_P] plane, the scapular rotations of the simulated X-ray projection were determined for the upper ridge of the scapular spine, indicated by the line through TS and AC, the lower ridge of the scapular spine through TS and AA, and the medial ridge of the scapula through TS and AI. The projection angles for the full range of arm abduction are shown in Fig. 3.

The 3-D movement of the upper ridge of the scapular spine, TSAC, resulted in a projection range of 23–88° during arm abduction. The $SH_{2\text{-}D}$ of arm abduc-

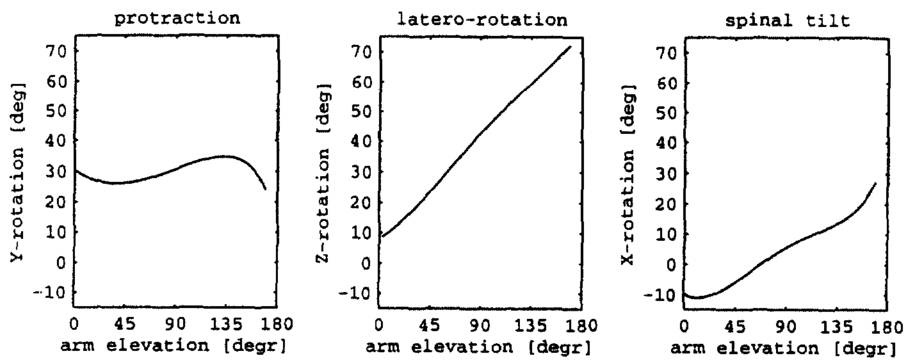

Fig. 2. The 3-D positions of the scapula during an arm elevation in a plane, 30° endo-rotated with respect to the frontal plane. The orientation is expressed by means of Cardan angles in the y–z–x order around the local axes of the scapula: x_S: The vector pointing from the trigonum spinae landmark to the angulus acromialis landmark. y_S: A vector perpendicular to the x_S-axis in the plane of the trigonum spinae, the angulus acromialis and the angulus inferior pointing upward. z_S: A vector perpendicular to the x_S and y_S axes pointing backward. The initial position of the scapular coordinate system is aligned with the global coordinate system.

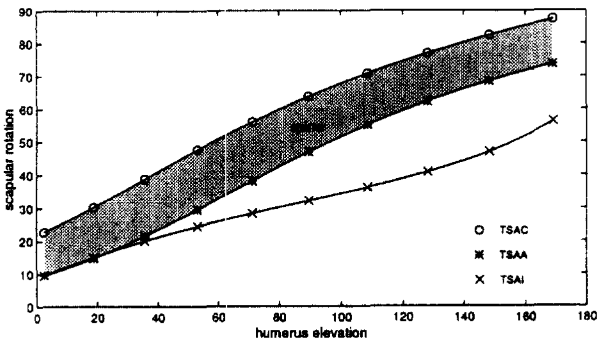

Fig. 3. The 2-D scapulo-humeral rhythm obtained from a simulated antero-posterior X-ray projection of a 3-D recorded shoulder abduction in a 30° endo-rotated arm elevation plane with respect to the frontal plane. The angles of the scapular spine, TSAC & TSAA, are determined relative to the horizontal x_P-axis; the angles of the medial scapular ridge, TSAI is determined relative to the vertical y_P-axis. The marked space between both curves of the scapular spine indicate the possible area in which the motion of the scapular spine can be defined.

tion over scapular rotation $\Delta\theta_A/\Delta\theta_S$ is 2.6. The projection pattern of the lower ridge of the scapular spine, TSAA, runs parallel to the upper ridge, although it is shifted about $-13°$, resulting in the same rhythm ratio of $\Delta\theta_A/\Delta\theta_S = 2.6$. The range of rotation of the medial scapular ridge, TSAI, is relatively small and results in a $SH_{2\text{-}D}$ of $\Delta\theta_A/\Delta\theta_S = 3.6$. The same rotation of the scapula resulted in different $SH_{2\text{-}D}$ values, as different scapular ridges were used for the quantification of the scapulo-humeral rhythm.

The relative orientation of the subject with respect to the X-ray apparatus was such that the recording was perpendicular to the frontal plane of the subject. the orientation of the subjects in previous experiments varied from this antero-posterior recording, to recording in a plane more perpendicular to the plane of the scapula in the anatomic position, Table 1. Although the position of the subject can be well defined, the orientation of the scapula in the X-ray setting will differ within a group of subjects, because of differences of the geometry of the shoulder bones, ligaments and muscles [14–16].

The effect of varying orientation of the scapula on the scapulo-humeral rhythm was simulated, Fig. 4. The orientation of the 'subject' varied between $-10°$ and $+35°$, indicating the rotation around the vertical y_G-axis and 0°, indicating a subject position in which the frontal plane was perpendicular to the camera axis, i.e. an antero-posterior recording. The scapulo-humeral rhythm for the upper scapular spine, TSAC, was determined for 10 initial orientations. The 0° orientation resulted in $SH_{2\text{-}D} = 2.6$, as calculated in the antero-posterior recording of Fig. 3. In this recording the relative motion of the scapular spine was the largest, resulting in the lowest scapulo-humeral ratio. Also, the sensitivity for small deviations of the subject orientation with respect to the camera, the derivative of the curve, is least at the 0° recording angle. At the recording angle of 30°, the excursion of the upper ridge of the scapular spine was reduced by a factor 0.74, resulting in a $SH_{2\text{-}D} = 3.5$.

4. Discussion

The $SH_{2\text{-}D}$ depends on the choice of the scapular ridge. This again illustrates the non-planar motions of the scapula during arm elevation due to the morphology of the shoulder mechanism, and is also quantified by 3-D motion studies. The difference between the $SH_{2\text{-}D}$ quantified by the rotations of the medial ridge and the $SH_{2\text{-}D}$ quantified by the spinal ridges is obvious. Less obvious is the fact that the spinal ridge itself is liable for deviations in the scapulo-humeral rhythm. Both the upper ridge of the scapular spine, modelled by TSAC, and the lower ridge modelled by TSAA, show an equal scapulo-humeral ratio. However, the curves are shifted with respect to each other and enclose a surface. In this simulation experiment the ridges of the scapular spine were uniquely identified by the skeletal landmarks TS, AC and AA. The spinal ridge is a relatively large and irregular volume of bony tissue. Therefore, it is not possible to uniquely identify a single bony ridge on the X-ray recordings of the scapular spine. One would see a lighter area of bone mass containing two thin white lines, originating from cortical bone parallel with the camera axis. A change of projection angle, e.g. by scapular motions, will alter the position, the intensity and the shape of the lines found in the previous projection. Consequently, it is not possible to uniquely identify the upper ridge and the lower ridge of the scapular spine, but any line between both the structures is possible. Any combination of points in the shaded area between the scapular ridges of Fig. 3 can be identified. Thus, for a single 3-D relation of scapular and humeral angles during an arm abduction, Fig. 2, any $SH_{2\text{-}D}$ can be quantified enclosed by both the TSAC and TSAA curves, resulting in a scapulo-humeral rhythm of $2.1 \leq SH_{2\text{-}D} \leq 3.3$. An accurate alternative for the problem of landmark recognition would be the implantation of X-ray dense spheres which can uniquely be identified. By means of bi-planar recording, the 3-D motions of the scapula can be determined [18].

In previous experiments, the orientation of the subject with respect to the camera axis varied between 0° and 30°, Table 1. It is often thought that an angle of 30°, i.e. the scapular plane, is the optimal orientation for the recording of shoulder motions, as it is expected that the plane of elevation of the scapula, Fig. 2,

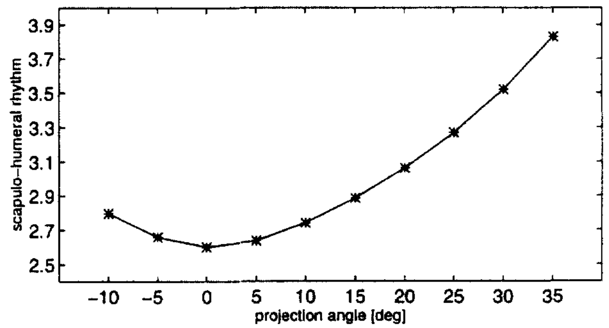

Fig. 4. the 2-D scapulo-humeral rhythm of the upper ridge of the scapular spine, TSAC, for different orientations of the subject with respect to the X-ray source. The recording was simulated for a full arm abduction motion. The projection angle corresponds with a subject rotation around the global y_G-axis. The antero-posterior simulated scapulo-humeral rhythm projection corresponds with 0°.

optimally coincides with the plane of recording [4,6,7,15,19]. In Fig. 4 it is shown for this typical example, that 0° instead of 30° is the optimal angle when using the scapular spine to indicate the scapular motions. The overall protraction angle during arm elevation, Fig. 2, which results from the combined displacement of the medial ridge of the scapula along the scapulo-thoracic gliding plane and the displacement of the AC joint, coincided best with the plane parallel with the frontal plane.

At the same time, a small deviation of this recording angle results in a relatively small deviation of the $SH_{2\text{-D}}$ because of the zero-slope of the curve at 0°, whereas a relatively high positive slope is found at the 30° recording angle. Recording at the 0° reduces the sensitivity of the $SH_{2\text{-D}}$ for small deviations in subject positioning.

The latero-rotation was the largest of the three scapular rotation angles, Fig. 2. The $SH_{2\text{-D}}$ is an approximation of this angle. The 3-D ratio of the arm elevation over the latero-rotation, $SH^{Rz}_{3\text{-D}}$, is equal to $(169°-2°)/(72°-8°)=2.65$. As the $SH_{2\text{-D}}$ is equal to 2.56, the approximation of the lateral rotation by means of the 2-D recording is obtained by multiplication with a factor 1.03, whereas the multiplication factor of the latero-rotation at the 30° recording angle is equal to 0.72.

5. Conclusions

The X-ray simulation study showed that the full range of the 2-D scapulo-humeral rhythm reported in literature, could be obtained from one single 3-D scapular motion during arm elevation. The inaccuracy is caused by the uncontrolled variability of scapular orientations with respect to the camera, and the problems of landmark recognition in the X-ray images. Therefore, the 2-D scapulo-humeral rhythm is an insensitive parameter which should not be used for inter-individual subject comparison.

Only when the data of the same individual are compared is it possible to observe differences between the scapulo-humeral motions due to medical treatment or different tasks. The spatial deformations due to subject morphology are constant, but only for the condition that the position of the subject with respect to the camera is equal. The best orientation of the projection plane would be the frontal plane instead of the so-called scapular plane.

If the 2-D method is used intra-individually, differences can be found between two recordings due to task or medical intervention. However, the interpretations of these differences are entirely dependent on the observer.

References

[1] Inman VT, Saunders JB, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surgery 1944; 26(A):1–30.

[2] Saha AK. Theory of the shoulder mechanism:descriptive and applied. Charles C. Thomas:Springfield, Illinois, 1961.

[3] Freedman L, Munro RR. Abduction of the arm in the scapular plane:scapular and glenohumeral movements. J Bone Joint Surgery 1966; 48(A.8):1053–510.

[4] Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Physiol Med Rehabilitation 1970;51:595–604.

[5] Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. Bone Joint Surgery 1976; 58(A):195–200.

[6] Bagg SD, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. Am J Phys Med & Rehabilitation 1988;67:238–45.

[7] Michiels I, Grevenstein J. Kinematics of shoulder abduction in the scapular plane:on the influence of abduction velocity and external load. Clin Biomech 1995;10:(3):137–43.

[8] Basmajian JV. Grants method of anatomy. 9th ed. Baltimore: Williams & Wilkins, 1975.

[9] Pronk GM. Three-dimensional determination of the motion of the shoulder girdle during humerus elevation. In De Groot G, Hollander AP, Huijing PA, Ingen Schenau GJ van, editors. Proceedings of the 11th ISB-Congress, Biomechanics XI-B, Amsterdam:Free University Press, 1987:1070–76.

[10] Johnson GR, Anderson GM. Measurement of three-dimensional shoulder movement by an electromagnetic sensor. Clin Biomech 1990;5:123–28.

[11] Pronk GM. The Shoulder Girdle. PhD Thesis, Delft University of Technology, Faculty of Mechanical Engineering and Marine Technology 1991. ISBN 90-370-0053-3.

[12] Johnson GR, Stuart pR, Mitchell S. A method for the measurement of three-dimensional scapular movement. Clin Biomech 1993;8:269–73.

[13] Van der Helm FCT, Pronk GM. Three-dimensional recording and description of motions of the shoulder mechanism. J Biomech Engng 1995;117:27–40.

[14] De Groot JH. Analysis of variance of the 3-D scapulo-humeral rhythm during elevation in the scapular plane. XVth ISB Congress 1995, Jyväskylä, Finland.

[15] De Groot JH. The shoulder:a kinematic and dynamic analysis of motion and loading. PhD Thesis, Delft University of

Technology, Faculty of Mechanical Engineering and Marine Technology 1998. ISBN 90-9011298-7.

[16] De Groot JH. The variability of shoulder motions recorded by means of palpation. Clin Biomech 1997;12(7/8):461–472.

[17] Bushong SC. Radiologic science for technologists. The C.V. Mosby Company, St Louis, 1988:ISBN 0-8016-1532-1.

[18] Högfors C, Peterson B, Sigholm G, Herberts P. Biomechanical model of the human shoulder joint II:the shoulder rhythm. J Biomech 1991;24:(8):699–702.

[19] Groot JH de, Valstar ER, Arwert HJ. Dependence of the scapulo-humeral rhythm on the arm velocity. Second World Congress on Biomechanics Amsterdam, 1994.